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ABSTRACT

A comprehensive monitoring system has been developed and implemented in the Sustainable Archetype House built at Kortright Conservation Centre of Toronto and Region Conservation Authority (TRCA) in Vaughan, Ontario, Canada. Over 300 sensors of various types covering sufficient energy monitoring details have been installed and calibrated in the twin houses. Data of interest, such as air temperature/relative humidity/flowrate, water temperature/flowrate, natural gas consumption, solar radiation, soil temperature/moisture and power consumption of individual component, are being collected for energy analysis. An expandable distributed data acquisition (DAQ) system has been adopted for monitoring and control purpose. LabVIEW platform is used to carry out data processing and post-analysis. Equations to evaluate mechanical systems were developed and implemented into the monitoring software. All data are recorded in the SQL server.

1. INTRODUCTION

In the cold climate region like Canada, residential and commercial buildings consume more than one-third of the total energy of the country. A number of converging market conditions are driving a consumer pull towards higher efficiency, better performing homes. Various advanced technologies have been adopted for efficient energy uses, less energy wastage and better home comfort. Government also attaches a great importance by providing encouraging initiatives, rules and regulations. The introduction of the new *Ontario Building Code* (OBC) format, including the *Energuide 80* alternative compliance option has led to renewed interest in higher performance mechanical systems. Higher efficiency standards, consumer awareness, and a pending increase in the *ENERGY STAR* compliance levels, have generally maximized insulation levels in current production housing standards of practice. The leaders in the residential construction sector are also starting to look at alternative mechanical systems and renewable energy sources as means to maintain their market position.

In Ontario, *Toronto and Region Conservation Authority* (TRCA) plays an important role in the education and promotion of green buildings. Along with the *Building Industry and Land Development* (BILD) Association, they have implemented the "Sustainable Archetype House" project at The Living City Campus at Kortright in Vaughan, Ontario, Canada. This Archetype Sustainable House is designed to demonstrate viable, sustainable housing technologies in the near and medium terms through research, demonstration, education, training, market transformation and partnership programs.

Several monitoring projects have been conducted in the past few decades. In the scope of research objectives, there are two types of monitoring techniques, i.e. single house monitoring, aiming to demonstrate new features of sustainable technologies and improving thermal performance of the existing houses; and side-by-side monitoring, typically comparing one house to the other in similar configuration to obtain detailed relative data of systems with similar functions. The tested results by former technique are usually compared with the published benchmark data, and assessment of overall improvement can be achieved. However, the detailed comparison between individual systems or equipment is not traceable. Examples of single house monitoring projects are "Solar Patriot" House in Washington, D.C., USA (Norton *et al.*, 2005), Discovery House in Loveland, USA (Hendron *et al.*, 2007) and Factor 9 home in Regina, Canada (Dumont, 2008). The benefits of side-by-side monitoring are featured not only with the overall assessment, but also with the instantaneous details in the performance of individual equipment. Examples of this monitoring technique and their features are listed in Table 1.

Table 1 Projects of side-by-side monitoring test

Reference	Location	Project	Major Features
Quirouette *et al.*, 1978	Ottawa, Canada	Four side-by-side houses	Overall impact of design packages, without focusing on the individual equipment.
Rayment *et al.*, 1993	UK	Two paris of identical prefab houses	Evaluating individual energy conserving measures.
Cohen, 2010	Milton, Canada	Mattamy Homes Green Initiative Project	Two houses equipped with different HVAC systems with advanced features. Each house was monitored by 25 sensors over one year period. Data was compared with modeling software for the total energy consumption, annual energy costs and total GHG emission.
Swinton *et al.*, 2001	Ottawa, Canada	CCHT project	Identical twin houses: one house is maintained at a constant level over time as a reference house, while the updated technologies are tested on its twin. Detailed monitoring plan with ~300 sensors (mostly temperatures and RH) for data collection on an hourly basis. Simulated occupancy control.
Barua *et al.*, 2009	Vaughan, Canada	TRCA project	Twin houses with different construction and mechanical systems. Detailed monitoring plan with +300 sensors of various types for data collection on a 5-second basis. Simulated occupancy control. Data will be used for benchmark analysis and modeling in various building simulation software.

The objective of this monitoring project is to implement a comprehensive monitoring system at the Archetype House. Identified sensors that can monitor energy flow of equipment or system were carefully calibrated before installation. The setup of the DAQ system was configured to minimize signal noise. National Instrument LabVIEW platform was adopted for coding the monitoring system. Equations used for the evaluation of different equipment and systems have been implemented in the software and the real-time data can be displayed/published through website to the public. The collected data, once verified, will be stored in the SQL server database for future analysis. With the detailed monitoring plan, it is possible to trace and fix some problems associated with the equipment operation and control.

2. MECHANICAL SYSTEMS OF ARCHETYPE HOUSE

In order to develop an adequate monitoring system, the configuration of mechanical systems in both houses should be reviewed. The details of the structure and envelop of the houses can be found in the paper by Dembo *et al.* (2010). The archetype house has two semi-detached houses: House-A (on the left in Figure 1) is designed to demonstrate best practices and technologies that are currently available and House-B (on the right) is designed for sustainable technologies that will be practiced in the near future. A garage is attached to each house. An In-law suite is built above the garage of House-B. A total of 19 mechanical systems were evaluated, for which advanced systems like ground source heat pumps (GSHP), solar domestic hot water (DHW) systems and fuel cell and other co-generation systems etc. were considered. The selection of mechanical systems was based on 5 criteria, i.e. total annual energy consumption, total annual GHG emission, total anuual energy cost, and first capital and life-cycle capital costs of mechanical system (Fung *et al.*, 2009). Each of the two selected mechanical systems and their features of the twin houses are given in Table 2.

Figure 1 South west view of the Archetype sustainable twin houses

Table 2 Mechanical features of Archetype twin houses

Features	House-A	House-B	In-law Suite (House-B)
Solar collector	Flat plate collectors	Evacuated tube collectors	From House B
PV cell	No	4 kWp	No
Wind turbine	No	3 kWp	No
Heating and/or cooling	Two-stage air source heat pump packaged with AHU	Ground source heat pump with horizontal loops, desuperheater and buffer tank	From House B
	Wall mounted mini combo gas boiler	Stirling engine micro-cogeneration unit with buffer tank	From House B
DHW system	Flat plate collector with one tank system	Evacuated tube collector with preheat tank and TOU based electric backup and GSHP desuperheater on the auxiliary tank, and auxiliary heat from cogen.	None
Ventilation system	HRV	ERV	HRV with “Solarwall” air heater
Auxiliary water heating	Mini gas boiler	Electric	From House B
Infloor heating/cooling*	Basement only	All three floors & basement	No
Heat recovery from drain water	Yes	Yes	No
Appliances	ENERGY STAR®	ENERGY STAR®	ENERGY STAR®
Lighting	Compact florescence bulbs	Compact florescence bulbs	Compact florescence bulbs
Solarwall	No	No	Yes

* for House-B only

2.1 HVAC System of House-A

In this sustainable house, a flat plate solar collector system is primarily used for DHW production. A wall-mounted mini boiler is used for auxiliary hot water production when solar collector alone is not sufficient. As a one-tank system, a DHW tank is set up for domestic hot water usage with the backup from the mini gas boiler. The mini gas boiler also provides auxiliary heating when the primary heating is not sufficient.

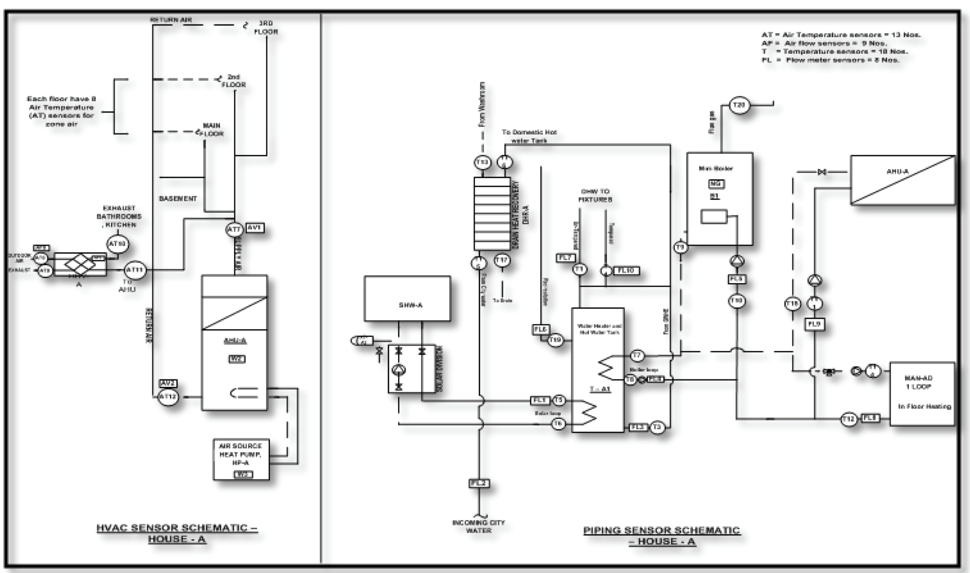

Figure 2 Layout of HVAC system and monitoring points in House-A

An integrated space-water heating system is installed in this house. By combining space and water heating in one unit, the system can lead to reduction in capital cost on the equipment and also increase the operation efficiency. A two-stage air to air source heat pump is used for space heating and cooling. This heat pump is integrated with the Air Handling Unit (AHU) with a variable speed fan, which supplies forced air for space heating/cooling. The radiant heating system is used in the basement for space heating. The mini boiler supplies hot water for the radiant heating in the basement, fan coil in the AHU for forced air heating to the main and second floors, and auxiliary backup for the DHW tank when needed.

A Heating Recovery Ventilator (HRV) is installed to recover waste heat from the exhaust air from kitchen and washrooms/bathrooms. The fresh air was pre-heated by the waste heat in HRV in the winter season. Another feature of the HVAC system in this house is the drain water heat recovery (DWHR) system. With this system a Powerpipe is set up in the main drain water pipe to recover significant amount of heat from the drain water. The detailed system flowchart for House-A is given in Figure 2.

2.2 HVAC System of House-B

An evacuated tube solar collector is primarily used for DHW production in House-B. More advanced technologies are applied to the HVAC system. A two-tank system is implemented: one tank is the solar hot water preheat tank and the other is TOU-based electric auxiliary hot water tank with additional heat from the GSHP desuperheater or from a micro co-generation system.

Multi-zoned infloor radiant system is adopted for space heating/cooling on all floors. The GSHP produces warm/chilled water by exchanging heat with the ground soil through two sets of horizontal loop buried in the yard. A micro co-generation system consisting of Whispergen Stirling engine is installed to simultaneously produce electricity and hot water suitable for domestic and space heating uses. A buffer tank is installed to hold warm/chilled water between the GSHP (or only warm water from micro co-generation system in heating season alternatively) and radiant conditioning system. In the cooling season, the buffer tank supplies chilled water to the multi-zoned AHU and/or the infloor system to remove heat from the returning air and/or to remove the heat sensibly in the room. Both the multi-zoned AHU and infloor system will provide enhanced zone control for thermal comfort and energy efficiency.

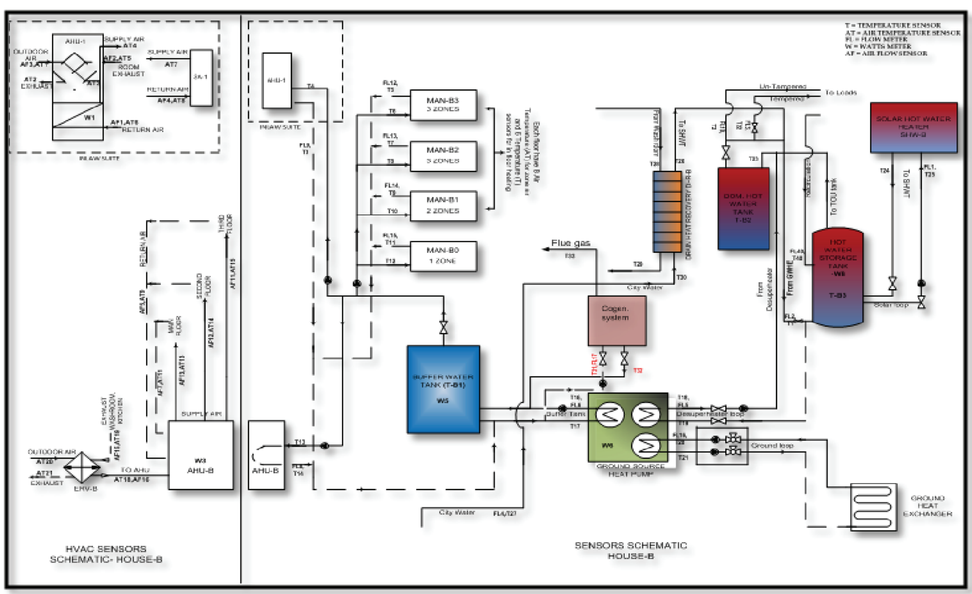

Figure 3 Layout of HVAC system and monitoring points in House-B and Inlaw suite

Other energy saving technologies adopted in the HVAC system in this house are: Energy Recovery Ventilator (ERV) that exchanges both sensible and latent heat between the exhaust and fresh air; a desuperheater that is attached to the GSHP to utilize superheated refrigerant generated from the compressor of the heat pump; a DWHR system is set up for recovery of heat from the drain water, hot water circulator with motion sensors on all basins demand switch in kitchen. The detailed system flowchart for House-B and the attached In-law Suite is given in Figure 3.

2.3 HVAC System of In-law Suite

The inlaw suite is a separate living room above the garage. The unique mechanical feature of this suite is the solar wall system, which preheats fresh air through solar air heater and supplies the warm air into the room. An integrated HRV and AHU unit WAS installed as the ventilation system. The main heating/cooling is provided from the main house's mechanical system through warm/chilled water.

3. MONITORING SYSTEM

In any monitoring project the following activities should be involved: projects planning, installation of sensors and DAQ system, calibration, ongoing data collection and verification, data analysis and reporting. The monitoring plan for the mechanical system is demonstrated in Figures 2 and 3, where detailed monitoring points are indicated.

3.1 Sensors

Over 300 sensors of various types covering sufficient energy monitoring details have been installed and calibrated. Data of interest are being collected for energy analysis, such as air temperature (AT)/relative humidity (RH)/flowrate, water temperature/flowrate, natural gas consumption, solar radiation, soil temperature/moisture and power consumption of individual component. A summary of monitored components and their required inputs are provided in Table 3.

Table 3 Assessment of components and required sensors

No	Component	Input Parameters	Sensors
1	Solar collectors (vacuum tube or flat plate)	USP grade Propylene Glycol temperature (inlet and outlet) and flow rate, solar radiation	RTD probe and flow rate sensor, Pyranometer
2	PV	Power generation, solar radiation at different tilt surfaces (horizontal, vertical and roof angle)	Wattnode sensor (bi-directional AC), Pyranometer
3	Wind turbine	Power generation	Wattnode sensor (bi-directional)
4	HRV/ERV	Air temperature and relative humidity (inlet and outlet), air flow rate (inlet and outlet), power consumption	Temperature (AT) & relative humidity (RH) sensors, pressure sensors with flow stations, Wattnode sensor
5	Integrated AHU/Air HP	Air temperature and relative humidity (to/from each zone), air flow rate (to/from each zone), power consumption	Temperature (AT) & relative humidity (RH) sensors, pressure sensors with flow stations, Wattnode sensor
6	Mini-boiler	Mass of natural gas, exhaust gas temperature, supply and return water temperature and flow rate (on return)	RTD, air flow rate sensor, natural gas meter, matched delta T probe
7	DHW tank	Water temperature (supply and return) and flow rate (on return), power consumption	Matched delta T probe and flow rate sensor, Wattnode sensor
8	GSHP	Water and anti-freeze temperature (supply and return) and flow rate (on return), power consumption, soil temperature and moisture	Matched delta T probe and flow rate sensor, Wattnode sensor, soil temperature and moisture sensor
9	Co-gen system	Mass of natural gas, exhaust gas temperature, Water temperature (supply and return) and flow rate (on return), power consumption	Matched delta T probe and flow rate sensor, natural gas meter, Wattnode sensor
10	Radiant floor	Water temperature (supply and return) and flow rate (on return)	Matched delta T probe and flow rate sensor
11	Solar wall	Air temperature and relative humidity (inlet and outlet), air flow rate (inlet and outlet), solar radiation	Temperature (AT) & relative humidity (RH) sensors, pressure sensors with flow stations, Pyranometer
12	Drain water heat recovery (DWHR)	Water temperature (supply and return) and flow rate (on supply)	Matched delta T probe and flow rate sensor
12	Ground soil	Soil temperature and moisture (various location), pipe surface temperature	Soil sensors, RTD sensors
13	Appliances	Power consumption	Wattnode sensor
13	Pump/fans	Power consumption	Wattnode sensor
14	Lighting and receptacle	Power consumption	Wattnode sensor

Data collected from various sensors are used for high level analysis. High level information worth of investigating includes energy balance, i.e. energy generation and consumption, equipment performance such as efficiency and effectiveness. The assessment of this information often requires temperature, relative humidity and flowrate on the supply and return of the system or loops. HRV/ERV, for example, are monitored by four integrated AT/RH sensors on the fresh air inlet, supply air outlet, return air inlet and exhaust outlet, respectively and two air flowrate sensors (combination of pressure sensor and flow station) on the inlet and outlet paths, respectively. By this way, the energy balance can be monitored and efficiency and effectiveness can be achieved. Similar approach applies to AHU, solar walls, solar collectors, radiant floor, GWHR, GSHP, DHW/storage/buffer tanks and co-gen system etc. The only difference is the replacement of the AT/RH sensor by the RTD probe in the hydraulic system.

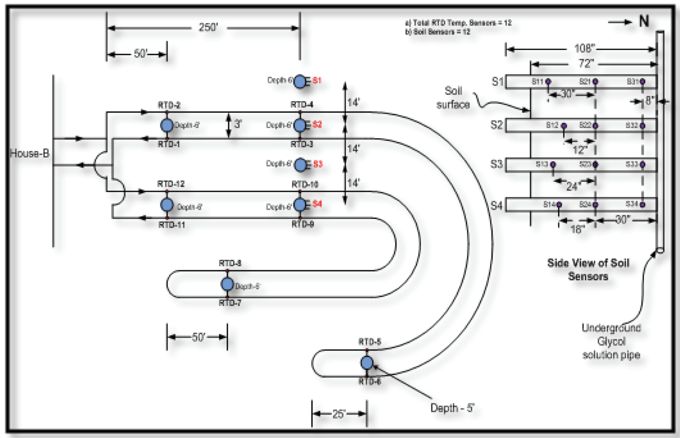

Figure 4 Layout of soil temperature and moisture sensors around the loop and RTD sensors on the loop

Power generation by PV, wind turbine, co-gen system and power consumption by all the equipment, lighting and appliances, are also important factors in energy balance equation. Wattnode sensor, which measures instantaneous power generation or consumption, is used to monitor power information in the above locations.

3.2 Calibration

Calibration is the process of mapping raw sensor readings into corrected values by identifying and correcting systematic bias. Sensor calibration is an inevitable requirement due to natural process of device decadence and imperfection. Calibration is one of the critical tasks in this monitoring project and considerable amount of time was allocated to this process to ensure the accuracy of data before the official data collection started.

The off-line calibration technique was applied, by which the collected data was treated as two components: raw sensor readings and data captured by high quality calibrators measuring the same set of readings at essentially the same positions and the same angles. The second set of data serves as the standard of what the sensors should measure. The goal of the off-line calibartion is to find a compact function that provides the mapping from the raw sensor reading to correct values.

HART Scientific 9102S handheld dry-wells and MICROCAL 20DPC calibrators were used to calibrate RTD probes and air temperature sensors, respectively. Hot-wire thermo-anemometer was used to calibrate the air velocity. Pressure sensors were calibrated by measuring mA output signal while shortcutting the differential pressure ports. Water flowrate sensors were calibrated in a close loop with the known amount of water flow. Pyranometer adopts the manufacture’s in-factory calibration data.

3.3 DAQ System

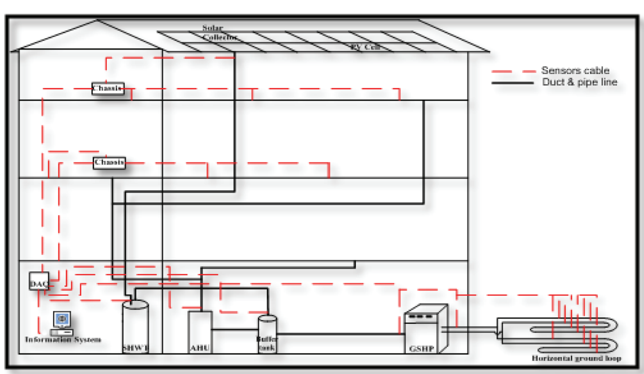

Figure 5 Layout of DAQ system in House-B

As the houses are extensively wired from different locations, a flexible and expandable distributed DAQ system is essential to obtain good quality data with minimal noises. The Compact Fieldpoint system from National Instruments has been implemented to process data collection. The central DAQ system is located in the mechanical room of the basement of each house, where the majority of the sensors are installed. In addition, each floor is equipped with a distributed chassis to collect air temperature and floor temperature data. The in-law suite of House B has a dedicated chassis to monitor various equipment and to process various signals. Another dedicated DAQ system was installed on the field to collect data of soil sensors and temperature sensors. All Compact Fieldpoints are connected to the central computer through Ethernet. An example of DAQ system setup and configuration with the central computer in House B is given in Figure 5.

3.4 Software and Database

The LabVIEW Development Suite 8.6 was used to develop the real-time monitoring system. The real-time project is adopted, and all the raw signals reading from sensors are converted to engineering units with the offset of calibration values. All signals are acquired at a sampling time of 5 seconds. Flowrate and power information contain both instantaneous rate and aggregated value. Equations that are used to evaluate the thermal performance of individual equipment have been developed and implemented in the LabVIEW program.

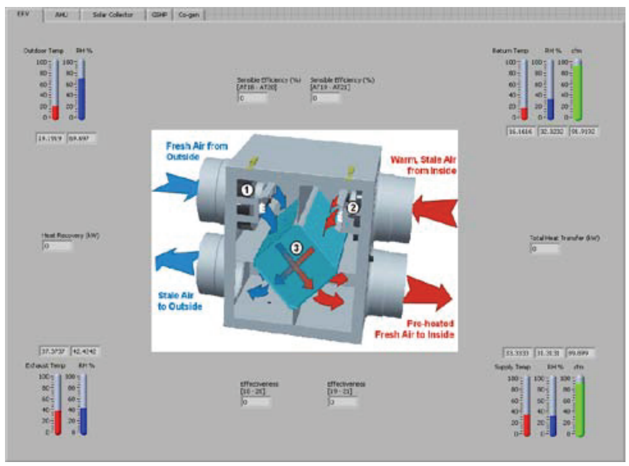

Figure 6 Sample of LabVIEW front panel implemented: ERV system at House B

Data collected from each sensor is assigned with a channel ID. All data are stored in the MS SQL Server 2008 database and the database structure is relational design rather than the “flat” design. The relational design refers to the database structure matching data by using common characteristics found within the data set, whereas with the “flat” design there is no structural relationship between the records. In the current database design, only three columns are used, i.e., DateStamp, Value and ChannelID. The Channel ID is defined in another table, referring to each individual sensor. By this way, sensor information is related to specific ID, which makes data management easier. This design is superior to the “flat” design, where data from all sensors (+300) are stored horizontally in the table. The relational design is more flexible than the “flat” design if adding or switching sensors is needed in the future. The modification on the DAQ system has no structural impact on the relational design, whereas the columns defined in the flat design have to be changed in order to record correct values.

4. CONCLUSIONS

A monitoring system has been implemented at Archetype Sustainable House in Vaughan, ON, Canada. The following tasks have been finished:

- Project plan was finished to locate various types of sensors on the system.
- Sensors were calibrated, installed and connected to the DAQ system.
- The DAQ system was connected with the central PC through Ethernet.
- LabVIEW code was developed to collect, proceed and store data.
- Equations used to calculate high level information were implemented in the code.

- Relational database was adopted in the SQL server to store data.
- Data acquisition and post-analysis are on-going. Preliminary data analysis has been carried out by Barua *et al.* (2010).

5. FUTURE WORK

As an on-going monitoring project, the following work will be carried out:

- Commissioning of DAQ system and collected data to ensure the accuracy of data.
- Obtaining the base case information without any occupant living in the house.
- Comparing the base case with the occupancy case where occupants of a typical family will live in the house in one summer month and one winter month. The effects of typical resident behavior on the energy performance of the house can be studied.
- Using building simulation software to simulate the energy performance of the house.
- Creating new components or subprograms to improve existing building simulation software.
- The data and the improved models can be used for benchmarking study of the normalized weather conditions.

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